BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Some Features of a Relay Satellite Air Traffic Control System - Case 101

DATE: May 31, 1967

FROM: C. A. Lovell

ABSTRACT

[redacted]

A study is made to show that a Satellite Air Traffic Control System can be developed from existing technologies. These technologies have been developed by NASA for Apollo and other space programs. The study system is a part of a world-wide system which is capable of surveillance of aircraft over land and sea equally well. Voice communications between ground and all aircraft under control of a sector is furnished under supervision of the ground station.

A partial error analysis is made which shows accuracies sufficient for all purposes including search and rescue which imposes the most stringent accuracy requirements.

Each control sector uses a cluster of four 24-hour satellites so disposed that not all four are coplanar at any time and that there always exists three of the four not coplanar with any of the aircraft under control. These conditions allow the aircraft position to be computed from the respective ranges from the aircraft to the three satellites.

Measurements on positions of several aircraft at one time are necessary to handle the large traffic load expected in the control sector within the next decade. One example of a way to accomplish this is given.

The system described solves one of the major air traffic problems of the present and the near future, that of en route control. A serious need for an all-weather landing system with a landing rate equal to the highest clear weather rate is possible and badly needed, but is not discussed in this memorandum.

The proposed system can control all commercial traffic expected in the next two decades. However, the immense volume of general aviation over U.S.A. would overload it in the presently described form.

A very short economic study using NASA development and launch costs shows the costs of a system with much higher capabilities than those of the present system, to be comparable with the costs of the present system. The satellite costs are decreasing rapidly while the present system costs are rising and the system is in danger of breaking down with increasing traffic load.

(NASA-CR-95563) SOME FEATURES OF A RELAY [redacted] SATELLITE AIR TRAFFIC CONTROL SYSTEM (Bellcomm, Inc.) 41 p

N79-71538

Unclas

Abstract (Cont'd)

A satellite system is the only known means for solving the surveillance and communications problems for aircraft flying over ocean routes.

[redacted]

BELLCOMM, INC.

SUBJECT: Some Features of a Relay Satellite Air Traffic Control System - Case 101

DATE: May 31, 1967

FROM: C. A. Lovell

MEMORANDUM FOR FILE

INTRODUCTION

It is recognized that air traffic over U.S.A. is outgrowing the capabilities of the control system. In spite of many studies made on the subject there is no consensus as to what should be done about the problem which has several important aspects:

(1) Congestion over land routes, especially near airports

(2) No all-weather landing system available

(3) No adequate communications or surveillance over oceans is available.

Many studies have been made since the advent of communications satellites, and it is generally agreed that the worldwide Air Traffic Control System of the future will be a satellite system. At the same time, almost all the development effort of FAA is being devoted to updating the present system, which may have to be discarded before it is finished.

It is a purpose of this memorandum to show by examples that no new technology breakthroughs are needed to implement a satellite air traffic control system and only straightforward development problems remain to be solved. Rather than an attempt to devise and describe a novel system, the present memorandum stays as close to existing technology as possible in order to emphasize this point. The time to start a new development on the surveillance system is now.

The system envisioned here uses a cluster of 24-hour satellites to relay ranging signals to aircraft and the transponded signals from the aircraft back to a control station on Earth. All measurements are made on the ground. The same satellites serve also as communication relay satellites between aircraft and ground stations and between the ground stations. Much of the discussion relates to methods of coping with the large traffic loads which result from a combination of large control sectors and large increases in air traffic expected within the next decade.

A study system is defined, its component duties are assigned in a reasonable manner, requirements derived and means described for meeting all the study system requirements.

Some explanatory material has been collected into Appendices A and B attached. These appendices should be scanned before reading the body of the memorandum.

STUDY SYSTEM FUNCTIONS

The following functions are assumed for system components for purposes of this study.

(1) Aircraft

Operation and navigation of the aircraft will be performed by the crew, using on-board equipments in accordance with a prearranged and approved flight plan. Any changes in flight plan desired by the captain are requested and approved by ground control. Any information developed on the ground indicating need for flight plan changes will be communicated to the aircraft by ground control.

(2) Ground Station

(a) Regular Functions

- Accept traffic from airports or other control sectors, maintain high precision en route surveillance and hand-over traffic to terminal airports or other control sectors.

- Maintain reliable air-ground, four-wire voice communications with all aircraft in sector on a switched channel basis with switching under ground supervision, plus an open channel for emergency use and for aircraft requesting assignment of switched channels.

- Acquire on the ground, data on aircraft positions, including altitude, at intervals depending on respective aircraft situations, without requiring active participation of the crew or use of measurements made by on-board instruments.

- Maintain permanent records of positions of all aircraft in sector as functions of time, updated at intervals suitable to the respective aircraft situations, with respect to the terminal airports, other aircraft or unfavorable weather.

- Process position data, predict occurrences of dangerous situations. Exercise control of aircraft only to avoid dangerous interference situations.

- Maintain up-to-the-minute weather maps of the sector and lists of dangerous areas, advise pilots of developing danger, and authorize changes in flight plans to minimize danger from weather conditions.

- Furnish fixes to aircraft on request.

(b) Emergency Functions

- Furnish backup navigational means to aircraft when on-board means become unreliable or inoperative.

- Furnish guidance (vectoring) to Search and Rescue craft and craft in trouble, to facilitate rescue operations.

- Reconstruct from permanent records kept at ground stations, course and speed of lost aircraft. Give circles of possible positions of ditched craft to SAR craft.

BROAD SYSTEM CONCEPT

The cluster of satellites provided to achieve the range measurements also provide communications between the ground and the aircraft under control. The communication function is widely understood and will not be discussed in detail here.

Three satellites determine a plane in three-space. If an aircraft is not in or near this satellite-system plane, the three distances between the aircraft and the respective satellites are sufficient to locate the aircraft position in three-space without using any data taken on-board the aircraft. It would be convenient if the satellites could be geostationary. However, this excludes a band around the earth near the equatorial plane from coverage by the surveillance system.

All 24-hour satellites in inclined orbits pass through the equatorial plane twice each 24 hours. Hence a 24-hour satellite system which is to be used continuously must have at least four satellites and two of them can not be geostationary. Two alternative configurations among many which are usable are represented by Figures 1(a) and 1(b). The configuration of Figure 1(a) consists of two geostationary satellites separated by 40° longitude and two 24-hour satellites whose nominal ground traces are in the form of a figure 8, crossing the equator midway between the geostationary satellites, and six hours apart in the figure 8.

Figure 1(b) shows a configuration consisting of one geostationary satellite and three in inclined orbits with a figure 8 ground trace which crosses the equator 20° in longitude from the geostationary satellite. The three satellites have the same nominal ground trace and are separated from each other by 8 hours in this trace.

In a world wide ATC system at least four clusters will be required in order to provide enough overlap between adjacent control sectors to facilitate the hand-off of traffic from one control to another. Figures 1(a) and 1(b) show clusters located to provide one control sector over U.S.A. and an adjacent sector over the Atlantic Ocean. The actual longitudinal placing may be done in a manner different from the Figures to meet desired control requirements. The satellite separations within a cluster is another design parameter that may be changed from those in the example to achieve desirable objectives.

COVERAGE OF EARTH'S SURFACE

The arcs on Figures 1(a) and 1(b) show the control sector boundaries drawn roughly so that all aircraft within the sector can be seen from all four satellites. Useful measurements can be made outside these boundaries using less than four satellites. There are three sets of conditions under which usable measurements can be made.

(1) Aircraft Visible to Four Satellites

This is the normal condition. The aircraft position can be calculated by solving three simultaneous linear equations which involve the four measured distances (See Appendix A).

(2) Aircraft Visible to Three Satellites

The aircraft position can be determined by solving three non-linear equations simultaneously, provided the aircraft and the three satellites are not coplanar. There is an ambiguity in the solution that is resolved if the position of the aircraft is known even to a very rough approximation.

(3) Aircraft Visible to Two Satellites

This condition may occur for aircraft near the earth's poles or in other boundary cases where one satellite is inoperative. The aircraft position may be determined if its altitude is known or can be obtained from the aircraft instruments. Solving three non-linear equations simultaneously locates the aircraft position except for an ambiguity that is easily resolved.

The normal mode is based on receipt of range signals via four satellites. The calculations are made on the basis of the number actually received. See Appendix A for further discussion of calculations and accuracies that may be achieved.

SURVEILLANCE SYSTEM

The major elements of the proposed system are shown schematically in Figures 3(a), 3(b), and 3(c). They are:

(1) The Ground Station consisting of:

(a) Antenna systems

(i) One interrogating antenna

(ii) Four high gain receiving antennas

(b) A multi-station ranging system

(c) Digital computers

(d) Storage and retrieval system

(e) Operators consoles and display systems

(f) Telephone channel terminal and switching equipment.

(2) A Cluster of Four 24-Hour Period Relay Satellites with orbits such that the four are never coplanar and at any time three can be chosen so that their common plane does not pass near the earth's surface. Each satellite contains:

(a) A power source

(b) A stabilization system

(c) An antenna system

(d) A multiplicity of coherent transponders

(e) Switch and control gear

(3) An Aircraft Fleet

Each craft under control of the sector is equipped with:

(a) A command receiver-decoder

(b) A coherent range signal transponder

(c) An antenna system

(d) A power plant

(e) Control switch gear

(f) Telephone station and channel terminal

(4) A Calibration System

This system consists of:

(a) Three earth locations accurately surveyed (one is assumed to be at the ground station)

(b) Two coherent transponders in well-surveyed locations

(c) Transponders in the satellites

(d) Computing and ranging systems in ground station.

ANCILLARY AND BASIC FUNCTIONS

In the process of carrying out its major functions, the ground station must perform a number of ancillary functions, the most important being:

(1) Measurement of Distances to Satellites

Consider Figure 3(a). Lines are drawn on this figure to represent this function only. An interrogating range sequence is sent out to the four satellites. Transponder t_{p+1} in each satellite locks its phase-locked loop to the received signal and transponds at a low signal intensity using a frequency not used elsewhere in the system. A high-gain, narrow-beam antenna at the ground station is trained on each satellite. Each antenna receives the signal transponded by that satellite. A range acquisition unit acquires and measures the phase. This gives a round trip time to each satellite and the distance ρ_i; $i = 1, 2, 3, 4$ is computed in each case.

(2) Calibration

Figure 3(b) indicates by means of the lines drawn, the signal paths of the calibration function for one calibration transponder. The PN sequence sent out captures the phase-locked loops of transponders T in each satellite. One of the transponders is chosen to transmit all interrogating signals while the others are turned off. The transmission is at a high signal level to interrogate aircraft and calibration sites. The two ground based coherent transponders at the calibration sites receive and transpond the signal. The transponders t_p+2 and t_p+3 in each satellite lock their phase-locked loops respectively to one of the calibrating signals and transpond at low level back to the ground station. The signals are received by separate antennas, phases of the returned signals are acquired by two sets of four range acquisition units and the PN signal phases measured. By subtractions of the distances between the ground station and each satellite the distances between each satellite and the two calibrating stations are determined. We have therefore the respective distances between each satellite and three known earth locations. From this the satellite positions may be calculated. After tracking each satellite in this manner for a period of time, the positions can be predicted for any future time with accuracies which are as good as the knowledge of the surveyed position locations.

(3) Aircraft Location

The location of an aircraft is the basic function. It is not different from the calibration except for the fact that the satellite positions are assumed known and the aircraft positions are calculated in these cases. The high level signals transponded through T capture the phase-locked loops of all transponders in aircraft under control. The normal condition of all aircraft is "transponder-off". The ground station addresses an aircraft over a command channel, orders it to turn the transmitter on using one of a set of specified frequencies. Figure 3(c) shows the signal paths involved in locating one aircraft. The transponded signal from the aircraft appears at each satellite with a small doppler shift which is different at each satellite. There is a transponder with its oscillator searching a narrow frequency range near each frequency used by an aircraft transponder. Hence this signal captures the phase-locked loop of the transponder using the same frequency in each satellite. The satellite transmits the transponded signal at low level to the ground station. This signal from each satellite is received by the high-gain antenna trained on that satellite. The signals returned to the four receiving antennas are grouped by frequency, sent to four range acquisition units, the respective phases are acquired and measured. The respective distances from the aircraft to the four satellites are computed. The aircraft position is then computed as described in Appendix A and recorded.

GENERAL METHOD OF OPERATION

In the normal method of operation, the ground station sends out two digital sequences repetitively:

(1) The PN ranging signal

(2) A string of address-command words.

These sequences are described in Appendix B. The bit rate in the PN signal is nearly one bit per micro-second. That of the address-command string is of the order of 2400 bits/second. The ranging channel band widths are about 2mhz/channel. The bandwidth of the command channel is about 3khz.

The transponder T in all of the satellites of Figure 3, are phase locked to a radio frequency carrier that is phase modulated by a PN sequence. However, only one of the transponders is turned on at any time. The choice is under control of the ground station.

When an aircraft is placed under control of a sector, two events occur:

(1) The ranging transponder is phase-locked to the PN sequence.

(2) An address code selected from the set described in Appendix B is assigned to the aircraft. This code is placed in the address register on the aircraft by the crew and verified by tests made by the ground station.

A subset of address-command words selected from the assigned set is formed at the ground station under control of a computer program and sent out in a continuous repetitive sequence. This sequence is replaced by another as soon as all of the measurements on that set of aircraft have been completed. This command sequence is relayed by satellite to all aircraft under control of the sector. The received sequence is fed into a 31 bit shift register in each aircraft. The contents of the address field in the shift register is compared with the aircraft address code. The command sequence has a start signal which initiates a match test between the aircraft code and the code in the shift-register address field when the start signal reaches a particular location in the shift register. When a match occurs, the contents of the command field are read out into a command register. We assume for this discussion that the command is to turn on the transmitter at a specified frequency. The transmitter switch will be turned off later by a timer. The timer will be reset to zero every time the aircraft address is received normally before it times out. When this address is removed from the command sequence, the timer is allowed to time out and the transmitter switch opens, stopping transmission from the aircraft.

Assume that the number of fixes to be made at one time is p. There are p aircraft transponding the ranging signal at about the same level as the signals sent out by T, each at a different frequency. There are p transponders in each satellite each having a free running oscillator with a frequency near one of the p frequencies. Each running oscillator is being swept in frequency over a narrow band that is wide enough to include the maximum doppler shift which can occur, but not wide enough to permit its phase-locked loop to lock on an adjacent signal. Thus, when the set of p aircraft begins to transmit, a transponder in each satellite locks its phase-locked loop to each frequency transmitted.

These p transponders in all satellites transmit at a level some 37 db below the level used by transponder T. The high-gain antennas at the ground station will receive and act on these signals. Each ground station antenna receives p frequencies, transponded by aircraft in addition to the other frequencies previously described. These p frequencies are selected in sets of four, differing from each other only by doppler shifts, from the four receiving antennas, fed to range acquisition units, the phases of the four return signals from each aircraft measured, and converted to distances.

RANGE CALCULATIONS

Let ρ_1, ρ_2, ρ_3 and ρ_4 be the respective distances between the ground station and the four satellites. See Figures 3a and 3b.

Let d_1, d_2, and d_3 and d_4 be the round trip distances traveled by the PN signals returning from the aircraft via the four respective satellites.

Let r_{ij} represent the distances from satellite i to aircraft j. See Figure 3c.

Assume T_1 in the first satellite is used to interrogate the first aircraft in the set. Then

$$d_1 = \rho_1 + r_{11} + r_{11} + \rho_1 = 2(\rho_1 + r_{11})$$

$$d_2 = \rho_1 + r_{11} + r_{12} + \rho_2$$

$$d_3 = \rho_1 + r_{11} + r_{13} + \rho_3$$

$$d_4 = \rho_1 + r_{11} + r_{14} + \rho_4$$

These equations may be solved for r_{11}, r_{12}, r_{13} and r_{14} to give

$$r_{11} = \frac{d_1}{2} - \rho_1$$

$$r_{12} = d_2 - (\frac{d_1}{2} + \rho_2)$$

$$r_{13} = d_3 - (\frac{d_1}{2} + \rho_3)$$

$$r_{14} = d_4 - (\frac{d_1}{2} + \rho_4)$$

Thus it is seen that if one of the returned signals returns through the interrogating satellite, all the desired quantities are obtained from simple subtractions. The values r_{ij} are the r's used to compute aircraft positions in space as described in Appendix A.

SPECIFIC REQUIREMENTS--STUDY SYSTEM

(a) Traffic Requirements

For study purposes two control sectors are defined:

(i) Continental Americas and the Pacific approaches

(ii) The Atlantic Ocean, Western Europe and Western Africa.

These areas are outlined roughly in Figures 1(a) and 1(b). The sectors are defined to have considerable geographic overlap.

The peak traffic assumed for each of the sectors is 600 aircraft under surveillance at one time. This may be compared with a present peak of about 150 over the North Atlantic. A peak of 600 aircraft will certainly be encountered during the life of such a system, very probably before 1980. Therefore, it is believed to be a realistic figure for present purposes.

(b) Average Time Required to Make a Fix

Since the interval t required to propagate the ranging signals is shown in Appendix B to be between .47 seconds and .55 seconds, we take the average as .51 seconds. This delay is incurred in starting the measurement process.

Mr. R. L. Selden* has studied a signaling system in which he assumed one second is sufficient to lock up all the phase-locked loops and other machine functions and 3 seconds integration time. An innovation is introduced in which the PN signal components are acquired in parallel, thus making more efficient use of the integration time. If one measurement requires four seconds then a maximum of 900 fixes per hour is possible if the aircraft positions are measured one at a time. This measurement interval will be assumed in setting the multiple ranging requirements because the power radiated from the satellite is computed by Selden and will be used in a subsequent example.

A subsequent memorandum by Selden** assumes that code regenerators will be furnished in the aircraft. A power reduction from 54 watts to less than 5 watts is achieved if this equipment is added in the aircraft.

---

*A Second Communications and Tracking System For Application to Air Traffic Control", R. L. Selden, November 23, 1966.

**A Low Power Ranging System for Application to Air Traffic Control - Case 101, April 27, 1967.

(c) Multiple Ranging Requirement

It is shown above that location of the position of one aircraft by means of the assumed techniques will require about 4 seconds. At this rate it would require 2400 seconds to take the position of each of the 600 aircraft in the sector, if the measurements are made singly. The resulting rate of three observations of an aircraft in two hours is completely inadequate. It is assumed here that aircraft in the sector should be observed at an average of 5-minute intervals. This would require 7200 fixes per hour or two fixes every second on an average. This rate may be achieved if 8 fixes are made every 4 seconds. Hence, it is assumed that fixes will be made simultaneously on groups of 8 aircraft.

(d) Range Accuracy Requirements

Safe and efficient use of air space makes it desirable to stack aircraft at 1000 ft. intervals in altitude. If we assume 1000 ft. spacing and require of the system a resolution adequate to monitor this spacing, a relative accuracy requirement of ± 300 feet separation is required. This is the most stringent requirement. Since it is a relative requirement, uncertainties about exact satellite positions do not produce first order degradations of it. The most stringent absolute requirement is assumed to be ± 1000 feet. The strongest reason for this requirement is in SAR operations.

The ± 1000 ft. limit corresponds to about 2 range units as defined in Appendix B. Hence, the basic accuracy required of the system is the order of one range unit. This is one bit in the ranging sequence and requires about 2 mhz bandwidth in the ranging channels.

Relaxation of this requirement to say ± 3000 feet would make possible a reduction of satellite power, speed up of range measurement, or allow some combination of these as a trade-off.

(e) Communications Requirements

(i) Control Channel

A discrete command and control channel is required for two purposes:

Command the aircraft transponder to transmit the range sequence and specify the frequency it is to use.

Establish a voice connection between aircraft and the ground station over an idle channel and ring the mobile station.

We assume a 31-bit address command word constructed in accordance with the description in Appendix B. There are 20 command codes in the command set. Assuming 8 of these codes define 8 frequencies used by the adjustable transponder, 12 codes may be used for communications purposes. We assume for study purposes that this is adequate.

The number of command words is 20 and the total number of bits in a command sequence is 620. This sequence can be sent only 4 times per second over a voice band. This may be adequate for voice channel control but would add another average of .25 seconds to the time required to make a set of range measurements. It is probably better to separate the ranging control from the voice channel control and use separate channels for these functions. The alternative is to slow down the ranging functions when there is a heavy load on the telephone system.

It is further assumed that the voice channels are 4-wire circuits allowing a normal telephone type conversation to be conducted instead of the push-to-talk type of operation. Hence, a group of 12 channels must be transponded by the satellite in each direction, making a total of 24 channels for voice. These transponders are not shown in the figures of this memorandum.

SYSTEM PARAMETERS

(a) Antennas

(i) Ground Station

The transmitting antenna will be assumed to have a beam broad enough and a power level high enough to capture the transponders T and t_{p+1} in all satellites and to acquire phase locks on them.

The receiving antenna will be narrow beam (say 1° conical) with about 40db gain. One will be continuously trained on each satellite for ranging and communications.

(ii) Satellites

The satellite antenna should have conical beams about 18° double angle at the apex. These antennas substantially fill an earth-grazing cone and illuminate all of the earth's surface visible from the satellite. Such an antenna has about 18db gain.

(iii) Aircraft

The aircraft antenna should have a 180° beam pointing upward from a level flying aircraft. The main lobe is a surface of revolution with ideally constant gain at all angles of elevation above 5°. Such an antenna can have no more than 3db gain.

(b) Bandwidths

(i) Ranging Channel

The bit rate in a ranging channel is about 1 microsecond. The ranging channel will be assumed to be 2 mhz. The number of channel bands required is 2(p+4) and the total channel space in the frequency spectrum is 4(p+4) mhz.

(ii) Command Channel

A command word is 31 bits. A command sequence is p words or 31p bits. The sequence must be transmitted several times per second. If for example p=8 and 10 transmissions persecond are assumed, the bit rate in the command channel is 2,480/second and a voice channel is required. This example indicates that the command channel bandwidth should be that of one or more voice channels depending on the value of p required by telephone traffic loads.

(iii) Voice and Command Channels

If we assume a group of 12 voice channels per satellite, we have 48 channels maximum for voice use. We assign two of these channels for command use leaving ten for voice. Therefore, we can have as many as 46 two-way conversations between the ground station and aircraft if all four satellites are in use, or 34 if only three are in use. The actual demand for voice connections is not known but these numbers are probably in the right ball park.

(c) Stablization

The satellites need the same accuracy in stabilization as communication satellites. Either gravity gradient or spin stabilization may be used. The gravity gradient is preferred if the Advanced Technology Satellite tests programmed show it to be adequate when used in synchronous orbits.

(d) Frequency Allocations

(i) Ranging

In the study system fixes are made in groups of 10 (assuming two calibrating channels operating continuously). The total number of channels needed is 24. A total bandwidth of 2(p+4) X 2 megacycles is needed so that a total of 48 megacycles bandwidth is assumed. This bandwidth is assumed to be assigned in the region of 2.5 Ghz.

(ii) Voice and Command

Both the command channel and the voice channels are assumed to be 4-wire. Hence, 2 groups of 48 kc are required for each satellite or a total of 384 kc for 4 satellites. These channels are assumed to be assigned in the neighborhood of 250 mhz.

(e) Power Requirements

The power requirements at the satellite and aircraft have been computed by Mr. R. L. Selden* for ranging, command and one voice channel.

The results are given in Tables 1, 2, and 3 of the referenced memorandum. These tables are reproduced here.

*"A Second Communications and Tracking System for Application to Air Traffic Control" - Case 101, November 23, 1966.

TABLE 1

DERIVATION OF SATELLITE (AIRCRAFT) TRANSMITTER POWER

1.	Transmitter Power	P_T dBW
2.	Transmit Circuit Loss	-3.0 dB
3.	Antenna Gain (Satellite)	+18.0 dB
4.	Path Loss (2.5 GHz - 20 KNMi)	-191.8 dB
5.	Aircraft Antenna Gain	+3.0 dB
6.	Aircraft Receiver Circuit Loss Ranging Signal Modulation Loss	-2.0 dB -0.5
7.	Total Received Signal Power	P_T-176.3 dBW
8.	Receiver Noise Spectral Density (T_{SYS} = 460°K)	-202.0 dBW/HZ
9.	Transponder 1F Bandwidth 2.5 MHz	64.0
10.	Total Transponder Signal-to-Noise Required	-138.0 dBW
11.	Required I.F. Signal to Noise Ratio (M = 1.25 Radians)	-21.0 dB
12.	Total Received Signal Power Required	-159.0 dBW
13.	Satellite Transmitter Power Required P_T - 176.3	-159.0
		17.3 dBW
		53.7 WATTS

Adding a 6 dB pad for additional losses raises this number to approximately 200 watts. Additional losses might include reduced satellite antenna gain and pointing loss and signal polarization and losses.

TABLE 2

DERIVATION OF TRANSMITTER POWER REQUIRED AT VHF OF VOICE AND COMMAND

1.	Satellite Transmitter Power	P_T dBW
2.	Transmit Circuit Loss	-2.0 dB
3.	Transmit Antenna Gain	+18.0 dB
4.	Path Loss (250 MHz-20 KNMi)	-172.0 dB
5.	Receive Antenna Gain	+3.0 dB
6.	Receive Circuit Loss	-2.0 dB
7.	Polarization Loss	-2.0 dB
8.	Total Received Signal Power	P_T-157.0 dBW
9.	Receiver Noise Spectral Density (T_{SS} = 725°K)	-200.0 dBW/Hz
10.	Detection Bandwidth 3 KHz	34.8 dB
11.	Noise in Detection Bandwidth	-165.2 dBW
12.	Signal-to-Noise Ratio Required (rms - rms tone)	17.0 dB
13.	Required Received Signal Power	-148.2 dBW
14.	Required Transmitter Power $P_T - 157 = -148.2$	+8.8 dBW
		7.5 WATTS

The results of his calculations show

Ranging Power		54 to 200 watts
Voice and Command		7.5 watts/channel
	or	90 watts/12 channel group

Data on the system assumed by Selden is summarized in Table 3.

TABLE 3

SUMMARY - AIRCRAFT - SATELLITE SYSTEM PARAMETERS

FUNCTION	SATELLITE	AIRCRAFT
Voice and Command		
Frequency	250 MHz	250 MHz
Modulation	Single Sideband	Single Sideband
Transmitter Power	7.5 WATTS	7.5 WATTS
Receiver Noise Temperature	725°K	725°K
Antenna Gain	18.0 dB	3.0 dB
Signal-to-Noise Ratio	17.0 dB	17.0 dB
Information Bandwidth	3.0 KHz	3 KHz
Ranging		
Frequency	2.5 GHz	2.5 GHz
Modulation	PN/PM	PN/PM
Transmitter Power	50-200 WATTS	50-200 WATTS
Receiver Noise Temperature	460°K	460°K
Antenna Gain	18 dB	3 dB
Signal-to-Noise Ratio (in transponder 1F)	-21 dB	-21 dB
Bandwidth	2.5 MHz	2.5 MHz

Figure 5 shows a partial block diagram of one form of the system with approximate frequencies and power levels at which the satellite and aircraft equipments work, as well as the antenna gains and channel bandwidths.

These tabulated data are for the high level range transponders in the satellite and in the aircraft. The low level transponders in the satellite, although there are a number of them, operate at about 30 dB lower level and do not contribute appreciably to the satellite power drain even though there is a considerable number of them. It should be noted that only one satellite is transmitting at high power at any time. Hence, the average power drain per satellite is one fourth of that computed. This fact is useful if there is provided in each satellite an accumulator for solar power received. Such an accumulator is needed because each satellite will be in the shadow of the earth for some 72 minutes at a time and no solar power is received. The high power transponders should not be used during these times but the low level transponders must be used even when the satellite is in the earth's shadow.

(f) Interrogation Program

While an observation of an aircraft position every 5 minutes may be satisfactory for an average, there are many situations which require more frequent observations. Primarily these are cases of aircraft in more crowded air lanes near airports. Conversely, aircraft in sparsely traveled airways may require less frequent observations. There is an opportunity to insert the address of an aircraft in the command sequence 900 times per hour. A program can be devised for interrogating some aircraft more frequently and others less frequently as required by the respective situations provided the average load does not exceed the total capacity. Except for rare situations, a fix every two minutes should suffice as a maximum for subsonic jets and somewhat more frequent fixes might be needed for supersonic jets.

There are 900 four-second intervals in an hour and there is an opportunity to introduce the address of an aircraft in any one of these intervals. This gives adequate flexibility in the interrogation program. As the airways become more crowded and the number of aircraft interrogated more frequently increases, it may become necessary to either decrease the interval, increase the group size, or use some combination of the two.

COSTS

Some preliminary cost estimates for establishment and maintenance of an Air Traffic Control System have been made using satellite and launch costs experienced by NASA in their programs to date. These estimates are as follows:

Establishment Costs

	10^6 dollars
Systems Engineering (4 years)	10.00
Systems Development	30.00
Satellite Costs (10* @ 1.5 million)	15.00
Launch Costs (10* @ 8 million)	80.00
Ground Station Costs	35.00
Total	170.00

*Assumes 2 launch failures

Annual Costs

Replacement Launches (4 @ 9.50)	38.00
Operation and Maintenance Ground Station	72.00
Total	110.00

Aircraft Costs

2,000 aircraft @ $10,000 each	20.00

The aircraft costs are a pure guess. However, the transponder is quite simple and in a volume of some several hundred per year the $10,000 unit costs seem reasonable. In any event, it is a small part of the whole.

A 5-year cost estimate omitting aircraft conversion costs are summarized as follows:

Establishment costs	170.00
5 Years @ 110.00	550.00
Total	720.00

The cost to FAA of operating and maintaining the present en route control over U.S.A. alone for 5 years will be in excess of one billion dollars so the comparison is not unfavorable to the satellite system. Most of the annual savings is in controllers' salaries.

It is doubtful as to whether a comparison with present costs is very meaningful for overland routes because one system will not completely replace another.

Also, over-ocean routes have no coverage at all now whereas the figures above cover two sectors, U.S.A. and the Atlantic routes. The over-ocean sector cannot be adequately policed by an extension of the present FAA system.

Finally, the present system will not be adequate for control of supersonic jet traffic because of the very short times these jets will be within one control sector.

General Aviation

There is an understandable reluctance on the part of the FAA to scrap the investment in the present system exceeding a half-billion dollars. There will be more than 100,000 small aircraft in U.S.A. within the next decade. If any substantial fraction of these aircraft should fly instrument flight rules and add to the estimated traffic, the proposed system might become badly overloaded. No such problem exists for over-ocean routes.

A serious attempt should be made to convert the existing over-land system to assisting general aviation rather than discarding it if a satellite system is adopted to control commercial air traffic. The fractional area coverage will be less for the lower altitude traffic. However, the general aviation flights are shorter and the aircraft slower, and some way might be devised to render assistance to this large volume of traffic and decrease the mutual hazards which it creates.

AIRPORT CONTROLS

The greatest traffic congestion is found in the neighborhood of airports. There are two ways of decreasing this congestion:

(1) Exercise better control of arrivals

(2) Develop a landing system that can handle traffic in all types of weather at about the same rate.

The proposed surveillance system will help control the arrival rate but can do nothing to speed up the landing rate in bad weather.

An adequate all-weather landing system is badly needed and little progress has been made in the last two decades toward development of such a system. The present ILS system is a ground wave radio system and while these systems have been tuned to particular situations so that they are reasonably effective, they are vulnerable to varying phenomena that change the ground waves such as a long freight train on a nearby railroad or ships anchored in a nearby harbor. The present versions can produce disastrous accidents for these reasons. The safety aspects are presently maximized by imposing visibility limitations on ILS landings which cause serious congestions at airports and force use of alternate airports to the inconvenience of passengers.

If the transponder equipments required for the satellite surveillance are on board the aircraft, these equipments can be made to serve also as parts of a landing control system. Such a landing control system is not a part of this study however.

Summary - Comments

(a) The major problems of establishing a Satellite Air Traffic Control System are discussed and proposals for their solutions shown to be in the present state of the arts.

(b) The Satellite System is the only practical system for use over oceans. It is much superior to the ATC system presently in use over land because the extremely broad coverage of a control sector minimizes hand-offs and drastically reduces the number of controllers needed.

(c) If a world wide control system is established using one type of system the satellite system is by far the best choice, if not the only choice.

(d) A lead time of at least four years is needed to establish such a system. The engineering should be underway now.

(e) An en route surveillance system solves one of three major air traffic control problems. One other, an all weather landing system is equally important and badly needed. It does not appear to be forthcoming from extensions of the present techniques.

(f) General Aviation over land masses poses a third problem. To include it in the world wide system will change the load parameters drastically and require sophisticated equipments in all aircraft. This may be the best approach but a possible alternative is to use the present system for general aviation and a satellite system for carrier traffic.

10-CAL-trb

CA Lovell
C. A. Lovell

Attached:
Appendix A and B
Figures 1 through 5

APPENDIX A

Aircraft Position Calculations

Assume four satellites in space not all in one plane, but all on the surface of a sphere of radius h. Let their coordinates be (x_1,y_1,z_1), (x_2,y_2,z_2), (x_3,y_3,z_3) and (x_4,y_4z_4) respectively. Let an aircraft A have coordinates x,y,z. The four straight line distances between the aircraft and the respective satellites are given by:

$$
\begin{aligned}
r_1{}^2 &= (x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 \\
r_2{}^2 &= (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 \\
r_3{}^2 &= (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 \\
r_4{}^2 &= (x-x_4)^2 + (y-y_4)^2 + (z-z_4)^2
\end{aligned}
\tag{1}
$$

also since $x_i{}^2 + y_i{}^2 + z_i{}^2 = h^2$, $i = 1,2,3,4$

$$
\begin{aligned}
r_1{}^2 - r_2{}^2 &= 2(x_2-x_1)x+2(y_2-y_1)y+2(z_2-z_1)z \\
r_2{}^2 - r_3{}^2 &= 2(x_3-x_2)x+2(y_3-y_2)y+2(z_3-z_2)z \\
r_3{}^2 - r_4{}^2 &= 2(x_4-x_3)x+2(y_4-y_3)y+2(z_4-z_3)z
\end{aligned}
\tag{2}
$$

The determinant D, given by

$$
D = 8 \begin{vmatrix} x_2-x_1 & y_2-y_1 & z_2-z_1 \\ x_3-x_2 & y_3-y_2 & z_3-z_2 \\ x_4-x_3 & y_4-y_3 & z_4-z_3 \end{vmatrix}
\tag{3}
$$

is not zero because its vanishing implies the four satellites are coplanar. Hence, equations (2) may be solved for x,y,z.

When returns are received via three satellites only, the three non-linear equations may be solved for x,y,z using measured values of r_1,r_2,r_3. In this case there are two solutions, and it must be known at the control center which hemisphere the aircraft is in, in order to resolve the ambiguity. The solutions will be made by computers.

When returns are received via two satellites only, it is necessary to have a third relation between x, y and z in order to calculate the aircraft position. If the altimeter reading on-board the aircraft is transmitted to the ground station, then the relation

$$x^2 + y^2 + z^2 = (a+\delta a)^2$$

in which a is the sea level radius of the earth and δa is the altitude, measured aboard the aircraft, may be used and a fix obtained except for an ambiguity which can also be resolved rather easily.

Figure 2 shows three satellites of the four in configuration shown in Figure 1(a).

Consider this figure. The x,y plane is the equatorial plane and the z axis points to the north pole. The point S_1 on the x axis is the location of one geostationary satellite. The point S_2 is a second geostationary satellite separated in longitude from the first by an angle 2α. The point S_3 is a 24-hour satellite in an inclined orbit. The point A is the location of an aircraft (near the surface of the earth). The distances r_1, r_2 and r_3 are the respective distances from the three satellites to the target aircraft. The coordinates of the satellites are respectively:

S_1 (h,0,0)

S_2 $(h\text{Cos}2\alpha,\ h\text{Sin}2\alpha,\ 0)$

S_3 $(h\text{Cos}\alpha\text{Cos}\beta,\ h\text{Sin}\alpha\text{Cos}\beta,\ h\text{Sin}\beta)$

The coordinates of the Target Aircraft will be denoted as unknowns (x,y,z).

We have the following relations:

$$r_1{}^2 = (x-h)^2 + y^2 + z^2$$

$$r_2{}^2 = (x-h\text{Cos}2\alpha)^2 + (y-h\text{Sin}2\alpha)^2 + z^2$$

$$r_3{}^2 = (x-h\text{Cos}\alpha\text{Cos}\beta)^2 + (y-h\text{Sin}\alpha\text{Cos}\beta)^2 + (z-h\text{Sin}\beta)^2$$

If r_1, r_2 and r_3 are measured by any method whatever the coordinates of A(x,y,z) can be calculated by solving simultaneously the three quadratic equations. Solution of these equations can be accomplished by computer methods and will not be discussed further here.

There is, however, a question of composition of errors in measurement into errors of position location. Let dr_1, dr_2 and dr_3 be errors in measurement and dx, dy, and dz be the resulting errors in aircraft position. These error quantities are related by linear equations, obtained by differentiating the range equations:

$$r_1dr_1 = (x-h)dx + ydy + zdz$$
$$r_2dr_2 = (x-h\text{Cos}\alpha)dx + (y-h\text{Sin}2\alpha)dy + zdz$$
$$r_3dr_3 = (x-h\text{Cos}\alpha\text{Cos}\beta)dx + (y-h\text{Sin}\alpha\text{Cos}\beta)dy + (z-h\text{Sin}\beta)dz$$

$$\text{Let } \Delta = \begin{vmatrix} x-h & y & z \\ x-h\text{Cos}2\alpha & y-h\text{Sin}2\alpha & z \\ x-h\text{Cos}\alpha\text{Cos}\beta & y-h\text{Sin}\alpha\text{Cos}\beta & z-h\text{Sin}\beta \end{vmatrix}$$

Since x,y,z are points near the earth's surface, and the plane containing S_1, S_2 and S_3 does not pass near the surface, the point x,y,z cannot be coplanar with S_1, S_2, S_3 and

$\Delta \neq 0$ for all x,y,z of interest

Hence

$$dx = \frac{1}{\Delta}\begin{vmatrix} r_1dr_1 & y & z \\ r_2dr_2 & y-h\text{Sin}2\alpha & z \\ r_3dr_3 & y-h\text{Sin}\alpha\text{Cos}\beta & z-h\text{Sin}\beta \end{vmatrix}$$

$$dy = \frac{1}{\Delta}\begin{vmatrix} x-h & r_1dr_1 & z \\ x-h\text{Cos}2\alpha & r_2dr_2 & z \\ x-h\text{Cos}\alpha\text{Cos}\beta & r_3dr_3 & z-h\text{Sin}\beta \end{vmatrix}$$

$$dz = \frac{1}{\Delta}\begin{vmatrix} x-h & y & r_1dr_1 \\ x-h\text{Cos}2\alpha & y-h\text{Sin}2\alpha & r_2dr_2 \\ x-h\text{Cos}\alpha\text{Cos}\beta & y-h\text{Sin}\alpha\text{Cos}\beta & r_3dr_3 \end{vmatrix}$$

It will be noted that the coordinate errors dx, dy and dz are functions, not only of the range errors but of x,y,z, the satellite positions and the satellite position errors as well. Thus, the geometric factors dilute the basic accuracy.

Some specific calculations of the amount of this dilution, assuming the satellite positions to be known precisely, have been made by use of a computer routine for this configuration. The results are given here. Using the notation

2α = longitude angle between geostationary satellites

β = inclination angle of third satellite

$\delta = dr_1 = dr_2 = dr_3$

The following table was calculated.

α	β	$\frac{dx}{\delta}$	$\frac{dy}{\delta}$	$\frac{dz}{\delta}$	$\frac{\sqrt{dx^2 + dy^2 + dz^2}}{\delta}$
20°	20°	-.815	-.472	-.720	1.18
22.5°	22.5°	-.850	-.405	-.720	1.16
30°	30°	-.914	-.222	-.670	1.15

While these computations were made for one target point on the earth's surface, that point was not chosen for minimum accuracy dilution and is at $x=y=z=4000/\sqrt{3}$. The accuracy dilution due to geometric factors is small for the cases computed and does not vary greatly with aircraft position. Similar calculations made for the configuration of Figure 1(b) lead to results not appreciably different from those shown in this table.

APPENDIX B

The ranging technique proposed for the ATC system is Pseudo Random noise ranging based on the Apollo Unified S Band Ranging System. Its use here differs from the Apollo System in several respects:

(a) The upper and lower bounds on the ranges to be measured are relatively close to each other.

(b) Means must be provided to address a subset of the aircraft under control and cause those addressed to transpond the ranging sequence.

(c) Provision must be made for measuring several ranges simultaneously to:

  (i) Measure three or four distances required to locate the position of an aircraft in three-space;

  (ii) Locate the positions of several aircraft in time-overlapping operations.

(d) Two satellite relay transponders are inserted in the ranging loop and means to assure locking up the phase-locked loops must be provided.

(e) A system calibration means is needed.

The ranging codes and the address-command codes are discussed in this appendix. Other topics are treated in the body of the memorandum.

Time and Distance Limits

Consider Figure 4. The circle represents a projection of the Earth on a plane which passes through a synchronous satellite S and the center of the Earth. For rough calculations, the radius of the Earth is taken at 4,000 miles and the altitude of the satellite as 22,300 miles. The point P is located so that the line SP makes an angle of 5° with the local horizon. If the figure is rotated about the line OS, the chord C generates a plane that divides the Earth's surface into two parts. The part facing the satellite will be called the visible part of the Earth's surface.

The four 24-hour relay satellites used for ranging must be separated from each other by appreciable distances to give adequate precision in calculations of position from the measured ranges. Each satellite has a different part of the Earth's surface as its visible part. The part of the Earth's surface which is visible from all four satellites is the sector under control of the associated ground station. The ground station may be located anywhere within the sector, and it must be capable of fixing the position of any aircraft within the sector whether in flight or on the Earth's surface. It is desired here to get coarse upper and lower bounds to the distances travelled by ranging signals and to the time intervals which must elapse while the signals are being propagated.

The shortest distance occurs for the case where both the station and the aircraft are directly below a satellite. This is $4d_{min}$ (see Figure 4) and is 89,200 miles. The longest distance occurs in the case where both the station and the aircraft see the satellite at 5° elevation. This is $4d_{max}$ and is 102,800 miles. Hence, any total distance, d, travelled by ranging signals, must satisfy

$$89{,}200 \text{ miles} \leq d \leq 102{,}800 \text{ miles}.$$

If these distances are divided by the velocity of light the corresponding time limits are obtained

$$.47 \text{ seconds} \leq t \leq .555 \text{ seconds}.$$

A Proposed Ranging Sequence

The PN ranging technique and the properties of the ranging signals are described in "Digital Communications With Space Applications," Solomon W. Golomb, et al, Prentice Hall. The PN sequences are long sequences of binary bits which are repeated indefinitely. The repetition interval normally is greater than the round trip time of electromagnetic waves at the greatest distance to be resolved by the system. A PN sequence has the property that if two identical sequences are displaced one bit with respect to each other the numbers of matches and mismatches differ by, at most, one; i.e., the correlation is zero. Since all bits match when the sequences are in phase, these sequences are ideal for correlation detection. In such a detector the transmitted sequence is regenerated in arbitrary phase at the receiver and the phase of the generated sequence is shifted until a match is obtained with the phase of the returned ranging signal. The phase of the generated signal is then compared with the phase being sent out to determine the time that has elapsed since the returned signal was transmitted. From such measured times the required range measurements may be calculated.

In practice the long sequences used are constructed by logical combinations from a number of shorter sequences. The component sequences are matched against the returned signal, and when the phase of a component matches the phase of the same component in the returned signal, an easily recognized partial correlation is obtained. When all components are in phase with the corresponding component in the returned signal, the correlation is unity, and the phase of the returned signal is known to the nearest bit. It is easy to determine the round trip propagation time from the component phases.

For the satellite air traffic control system there are upper and lower bounds on the time required for a signal to be returned. The difference between these corresponds to 102,800 - 89,200 = 13,600 miles. It is known that all signal distances lie between these limits and must be resolved only within the 13,600 miles. This determines the length of the PN sequence required for the system.

Let one range unit correspond to the time required for light to travel 1000 feet and let this unit correspond to 1 bit in the PN sequence. There are 5.28 range units/mile and hence, the minimum number of bits in the sequence is 5.28 x 13,600 or 71,808 bits. Any sequence longer than 71,808 bits may be used.

Let the components of the sequence be

y = 1010---(clock) (2)

x = 01011 10 and repeat (7)

A = 11011 10001 0 and repeat (11)

B = 11001 11101 01000 0110 and repeat (19)

C = 00001 01011 10110 00111 11001 10 100 1 and repeat (31)

The system modulus, i.e., the length of the PN sequence is 90,706 bits.

The maximum number of component shifts required to acquire the phase of any returned sequence is 68. This is the sum of the numbers of bits in the component sequences with the clock excluded.

Let the sequence used for ranging in the ATC system be the logical function

$$f = xy + \overline{x}[(AB+BC+AC)\oplus y]$$

This sequence has a period of 90,706 bits and is suitable for making individual range measurements. However, the sequence does not, in itself, provide multiple-ranging capabilities, and must be used with the multiple satellite return paths to achieve it.

Address - Commands

A command channel is furnished over which commands may be sent to aircraft. Each command word is addressed to a particular aircraft, and only the addressee will recognize and act on the command.

Two classes of commands will be sent to aircraft equipments:

(a) To transpond the received ranging sequence specifying the frequency to be used.

(b) To establish telephone communication between the aircraft and ground station and ring the mobile station.

The command receiver will contain a shift register, a matching circuit, a command register and an address register. The aircraft address is stored in the address register. The sequence of command words is monitored continuously by all aircraft in the sector. The address-command word is composed of a sub-sequence of binary bits representing the address and another sequence representing a command.

When the code in the address part of the shift register matches that of the aircraft address code stored in the address register, the sequence in the command part of the shift register is read out into a command register and acted upon.

In order to make the detector-decoder in the aircraft simple, the address-command word is constructed of three binary subwords to accomplish respectively three purposes:

(a) To mark in a unique manner the beginning of a word in a sequence;

(b) To address an aircraft;

(c) To command the desired action.

For these purposes the command word Z^i is given the form

$$Z^i = SA^iC^i$$

where S is a start signal, A^i is a set of assigned addresses and C^i is a set of commands. The word Z^i will be constructed here somewhat arbitrarily to have the following set of properties:

(a) The number of bits is 31

(b) Each Z^i shall have 16 ones and 15 zeros

(c) The subword S = 01111110

(d) The sequence A^iC^i shall contain no runs of ones greater than 5.

This makes the run of six ones in S distinct. S is, therefore, an easily recognizable start signal.

For example, let the numbers of bits and ones be assigned in accordance with Table I.

TABLE I

WORD	BITS	ONES
S	8	6
A^i	17	7
C^i	6	3
Z^i	31	16

Adequately large sets of addresses and commands may be constructed to meet all stated requirements in the following way:

The command word will not be further restricted. Hence, there are 20 distinct commands possible.

One way to avoid runs of ones longer than 5 in the sequences formed by address words adjacent to command words is to require that the third bit from the right in every address word be a zero. This leaves only 8 bit positions to the right of the zero. Since there are only three ones in the command word, there can be no more than 5 ones to the right of the zero, hence no run of ones longer than 5.

There can be four different three-bit endings for the address word, namely 011, 010, 001, and 000. The number of address words having these endings respectively are $\binom{5}{14}$, $\binom{6}{14}$, $\binom{6}{14}$, and $\binom{7}{14}$; and the total number of distinct addresses is $\binom{5}{14} + 2\binom{6}{14} + \binom{7}{14}$.

$\binom{5}{14} = 2002$ none of which contain runs of ones greater than 5

$2\binom{6}{14} = 6006$ 18 of which have runs of 6, and none of which has a run of 7

$\binom{7}{14} = 3432$ 36 of which have runs of 6, and 7 have runs of 7

TOTAL = 11,440 - 61 = 11,379

These data on Z^i are summarized in Table II.

TABLE II

WORD	BITS	ONES	NUMBER IN SETS
S	8	6	1
A^i	17	7	11,379
C^i	6	3	20
Z^i	31	16	227,780

This, of course, is one set of a large number of possible usable sets of words that meet the specified requirements.

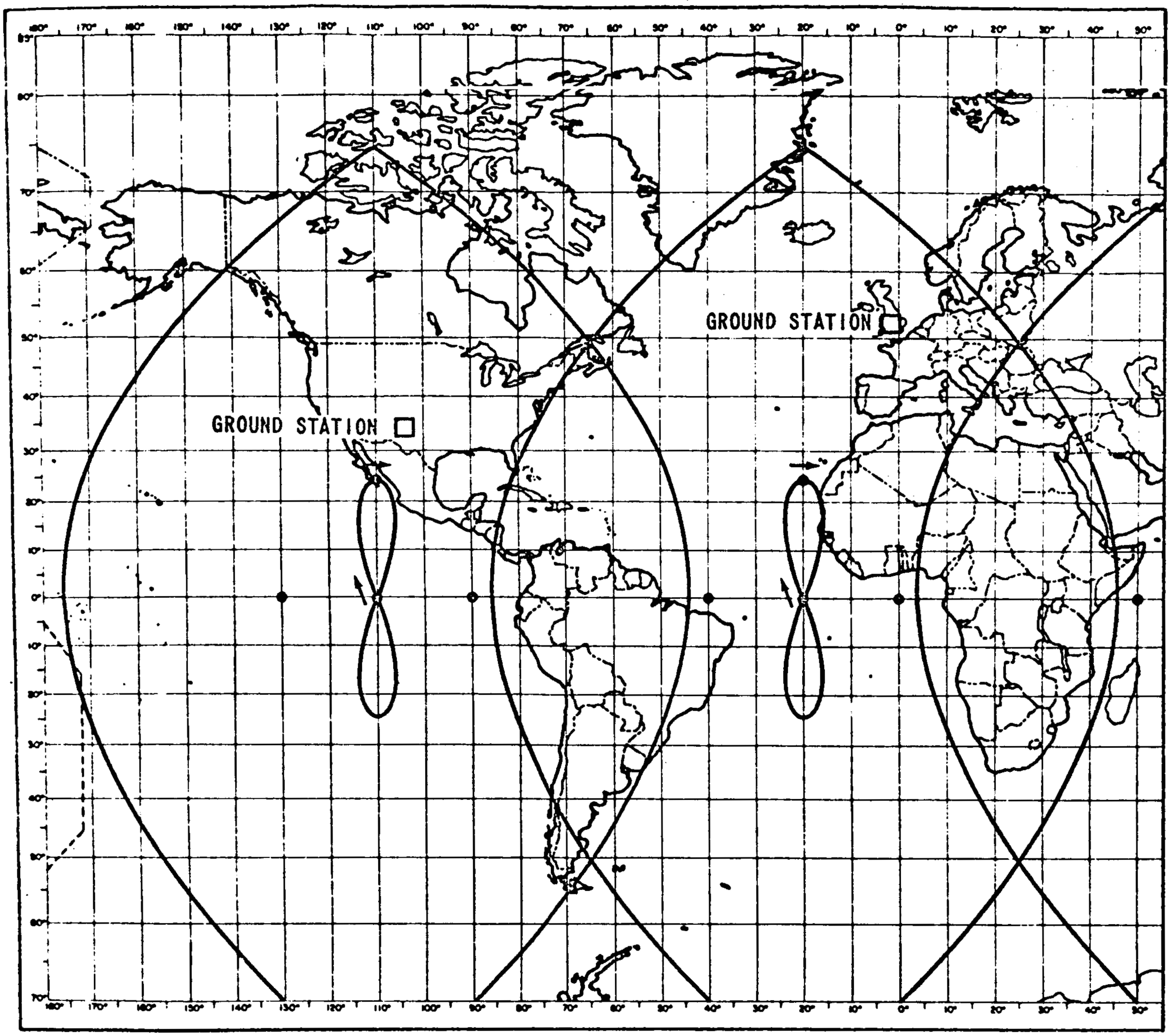

FIGURE 1(a)

SATELLITE AIR TRAFFIC CONTROL SYSTEM

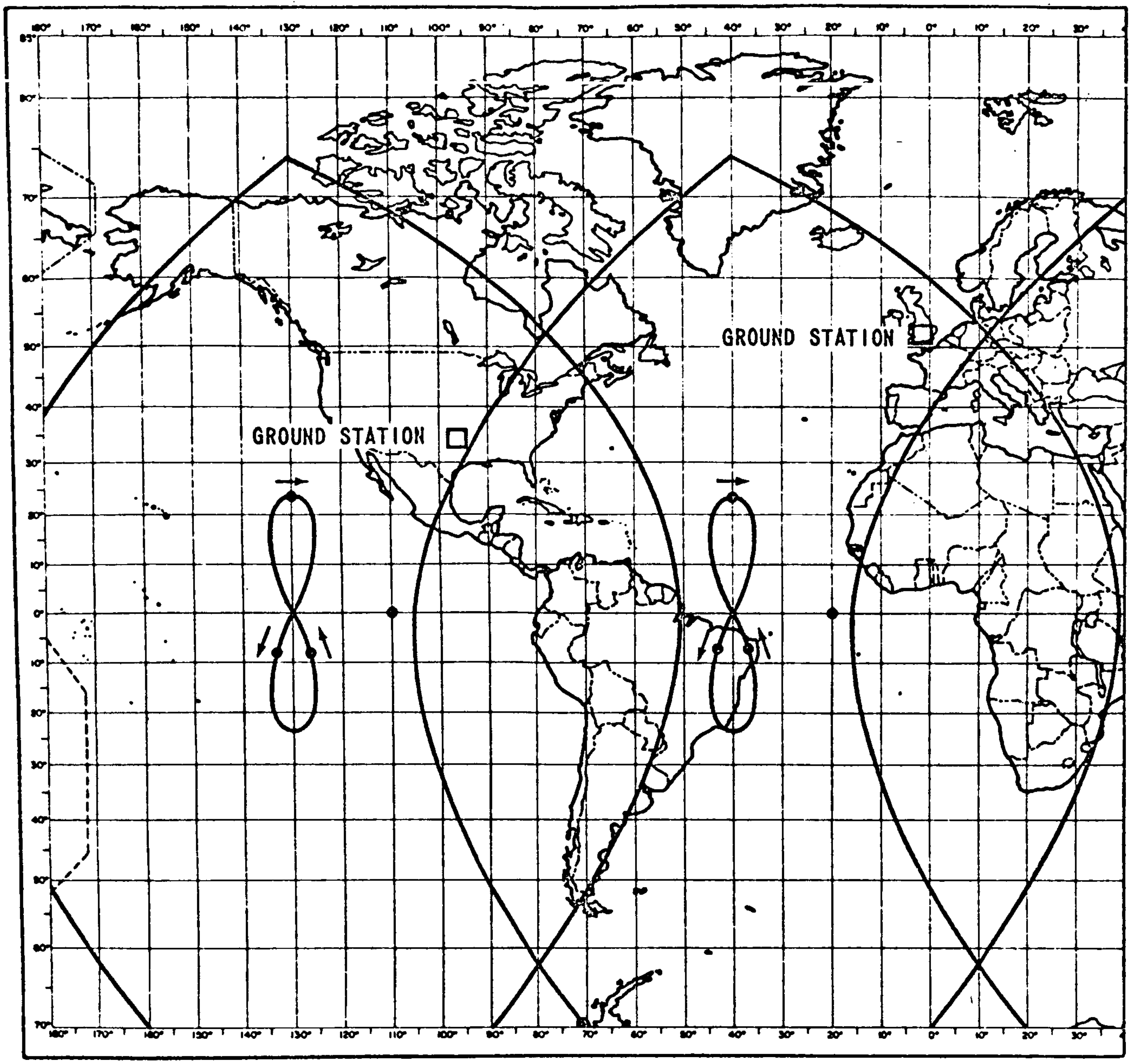

FIGURE I(b)

SATELLITE AIR TRAFFIC CONTROL SYSTEM

$$r_1^2 = (x-h)^2 + y^2 + z^2$$

$$r_2^2 = (x-h\cos 2\alpha)^2 + (y-h\sin 2\alpha)^2 + z^2$$

$$r_3^2 = (x-h\cos\alpha\cos\beta)^2 + (y-h\sin\alpha\cos\beta)^2 + (z-h\sin\beta)^2$$

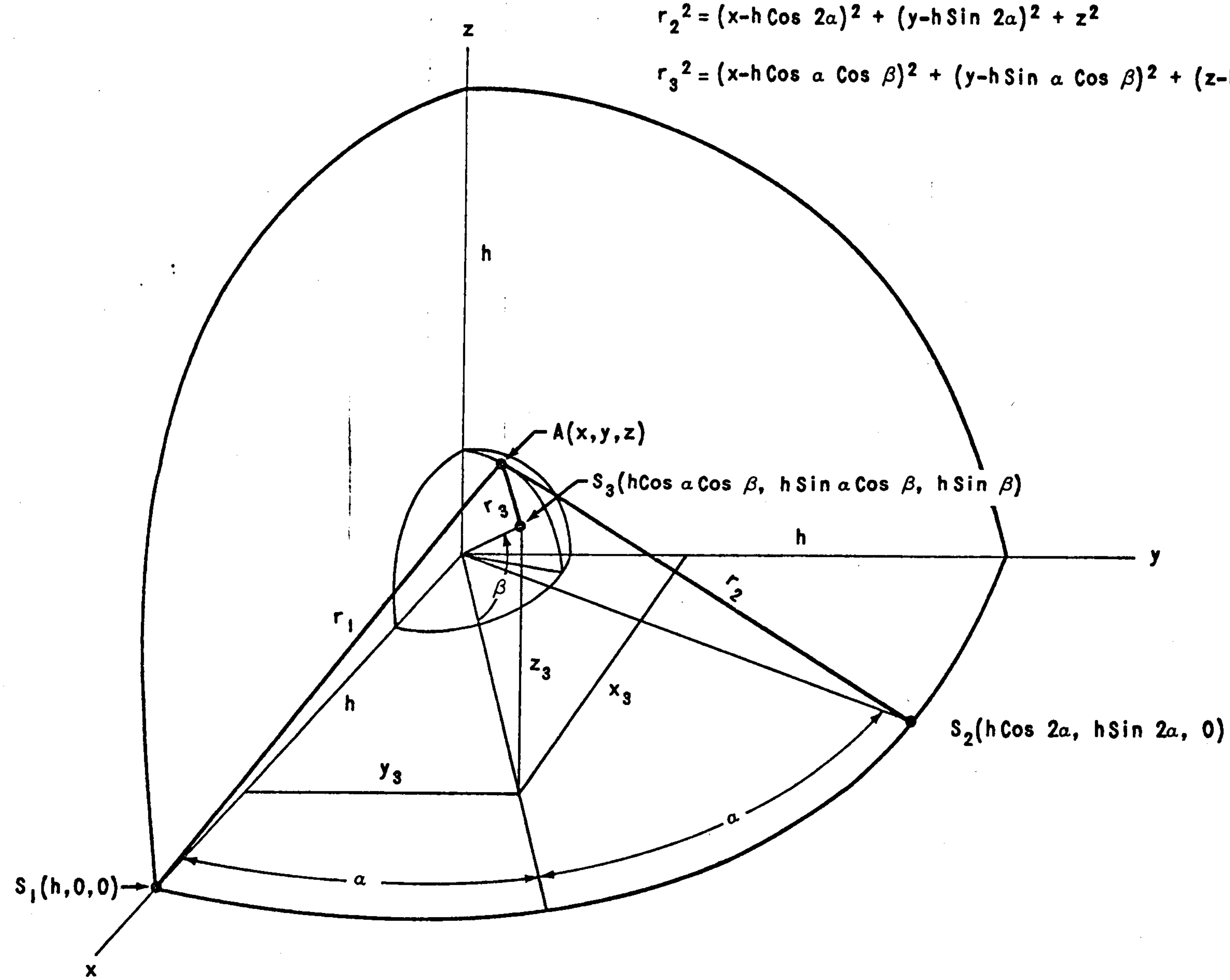

FIGURE 2

A SATELLITE CONFIGURATION

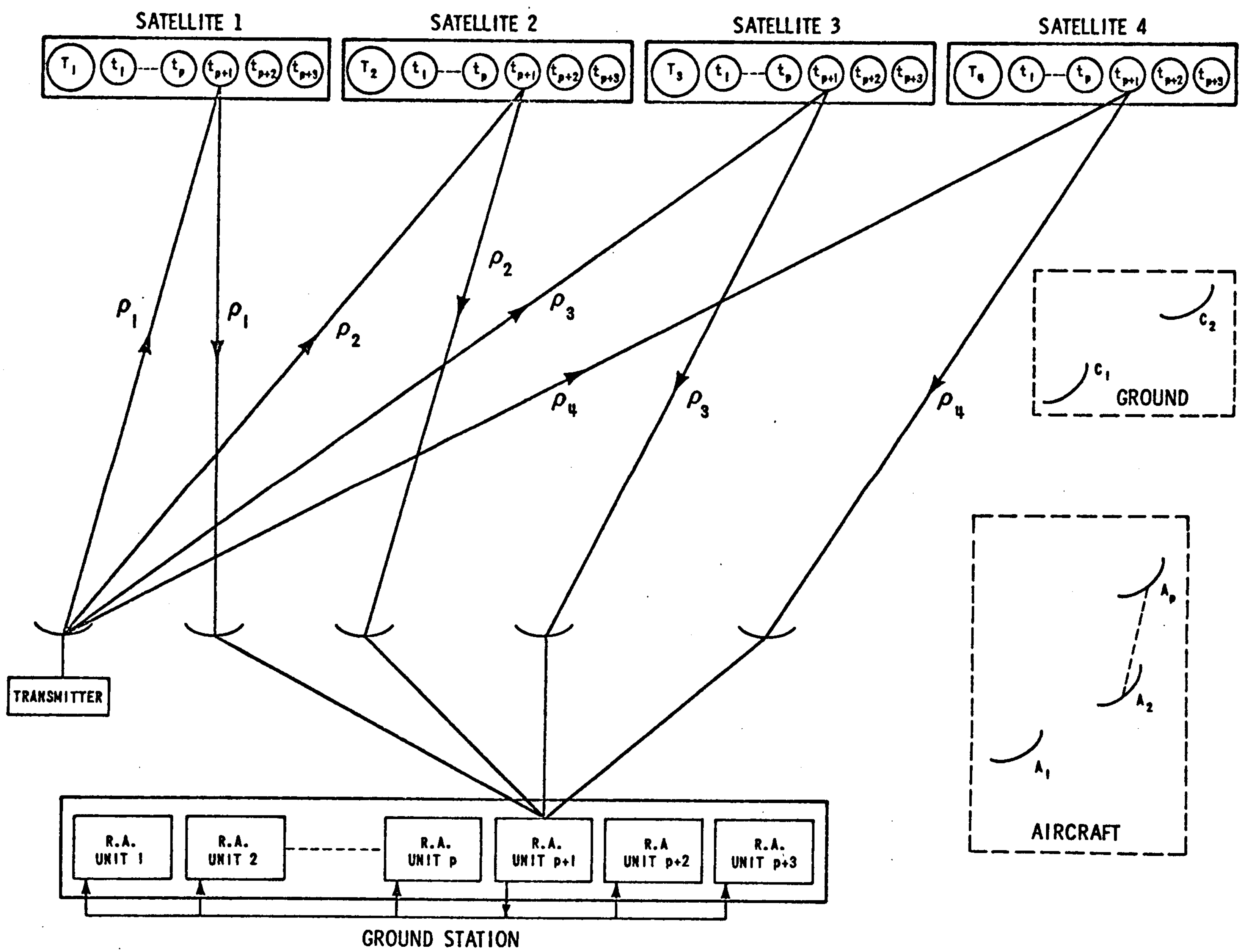

FIGURE 3a

SIGNAL PATHS FOR SATELLITE DISTANCE MEASUREMENTS

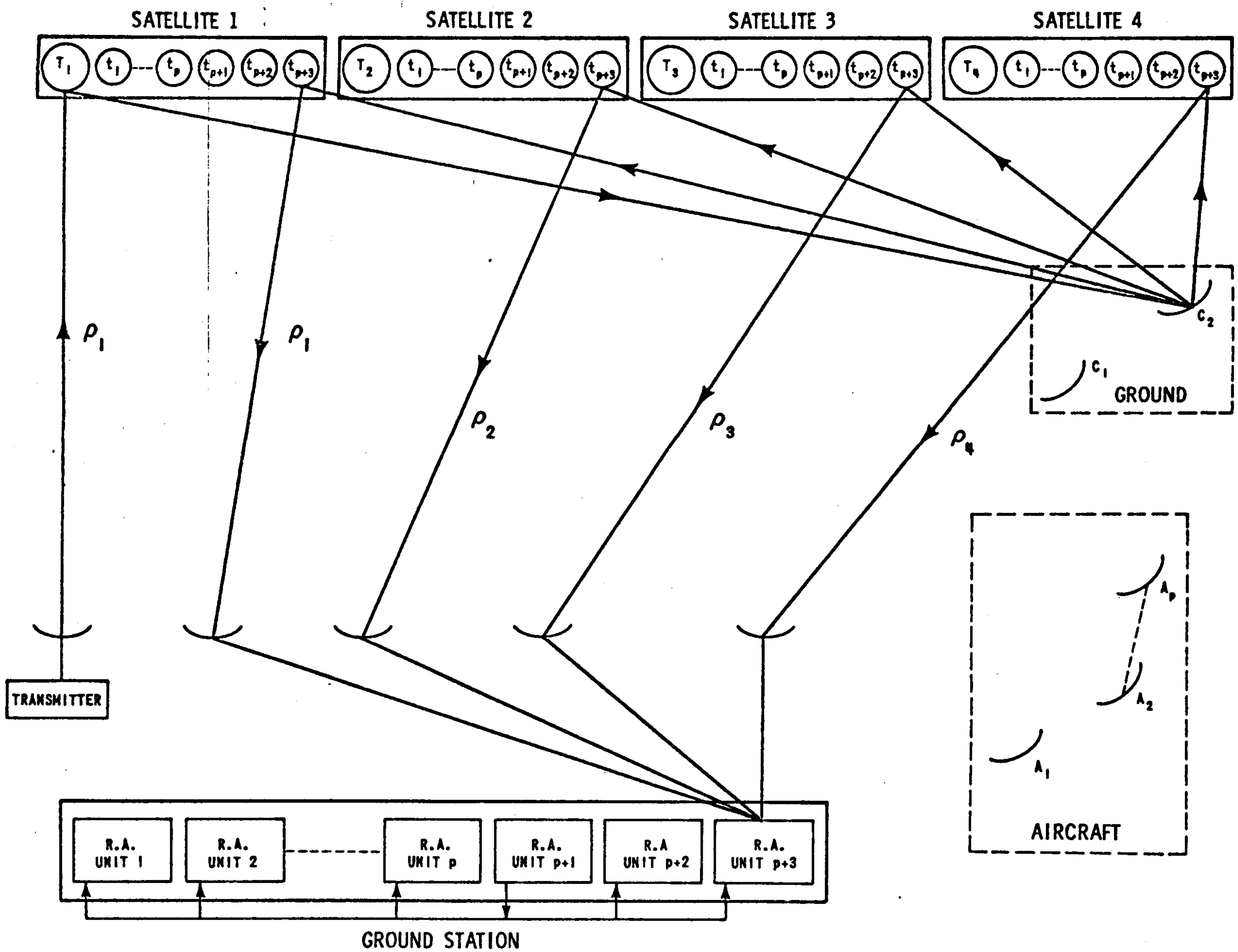

FIGURE 3b

SIGNAL PATHS FOR CALIBRATION

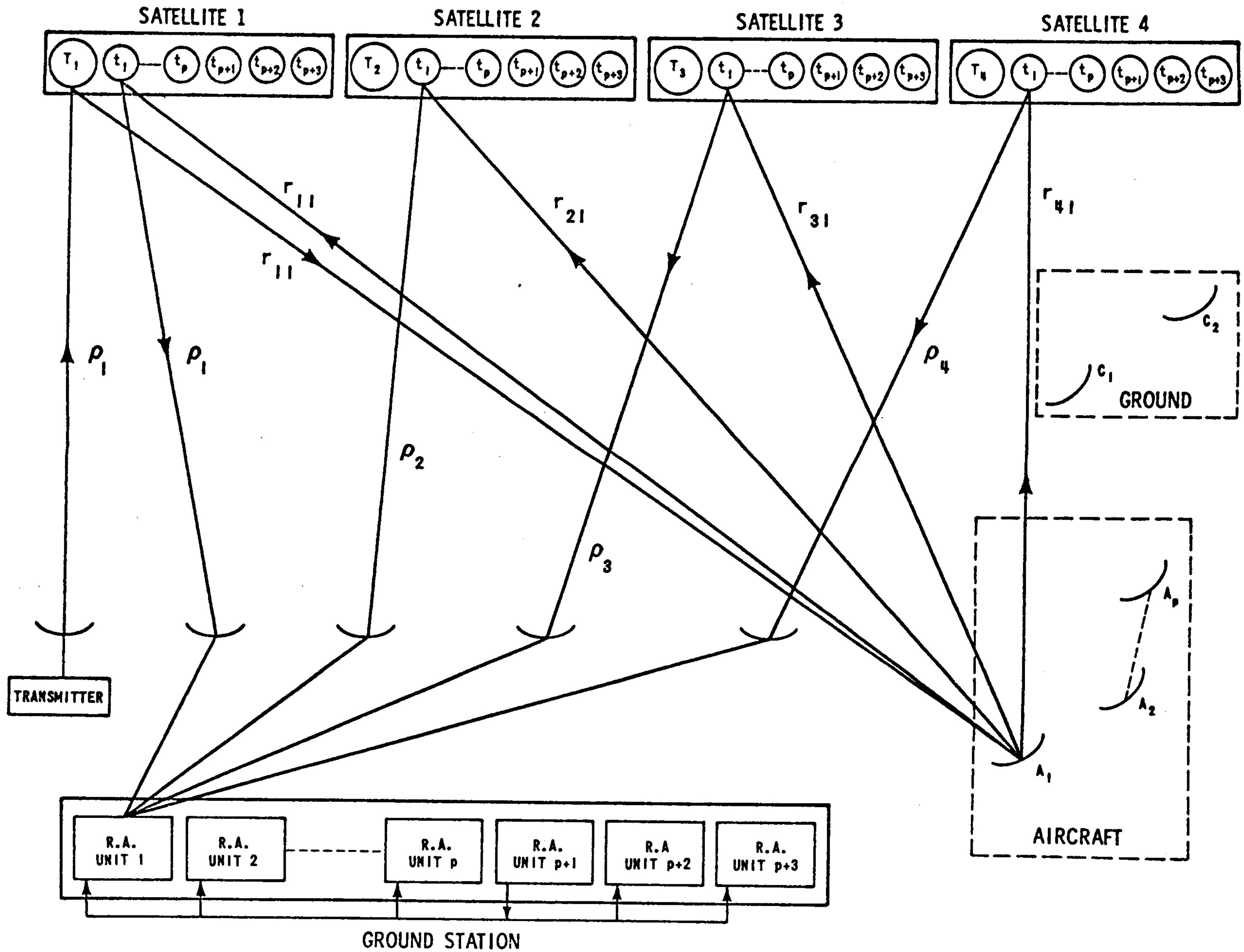

FIGURE 3c

SIGNAL PATHS FOR AIRCRAFT LOCATION

STUDY SYSTEM

Distances Involved

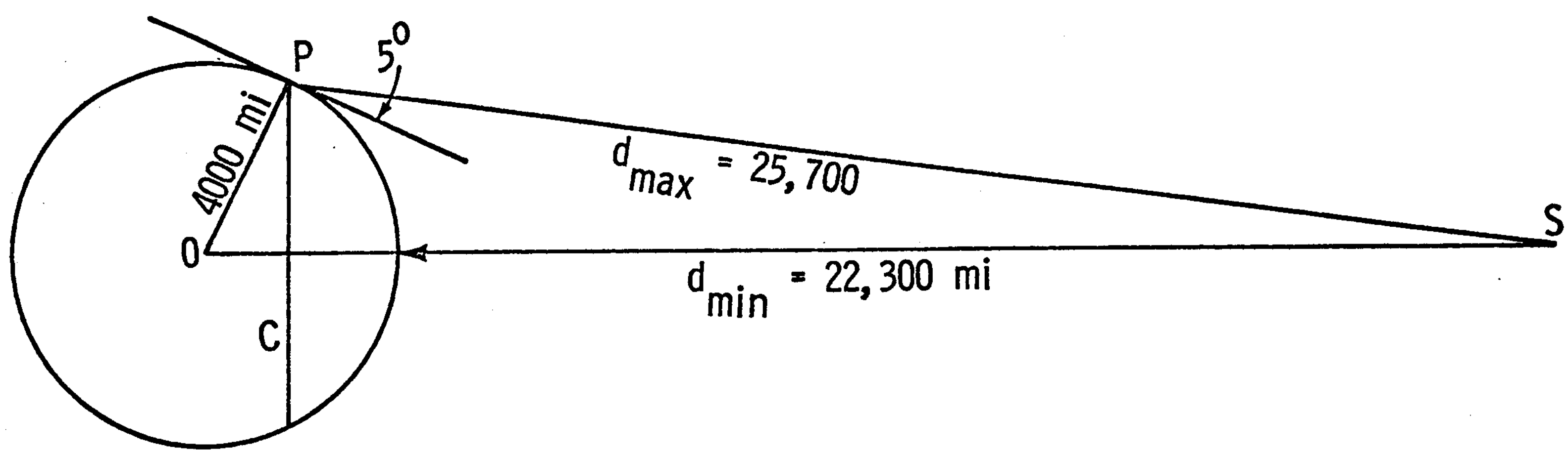

FIGURE 4

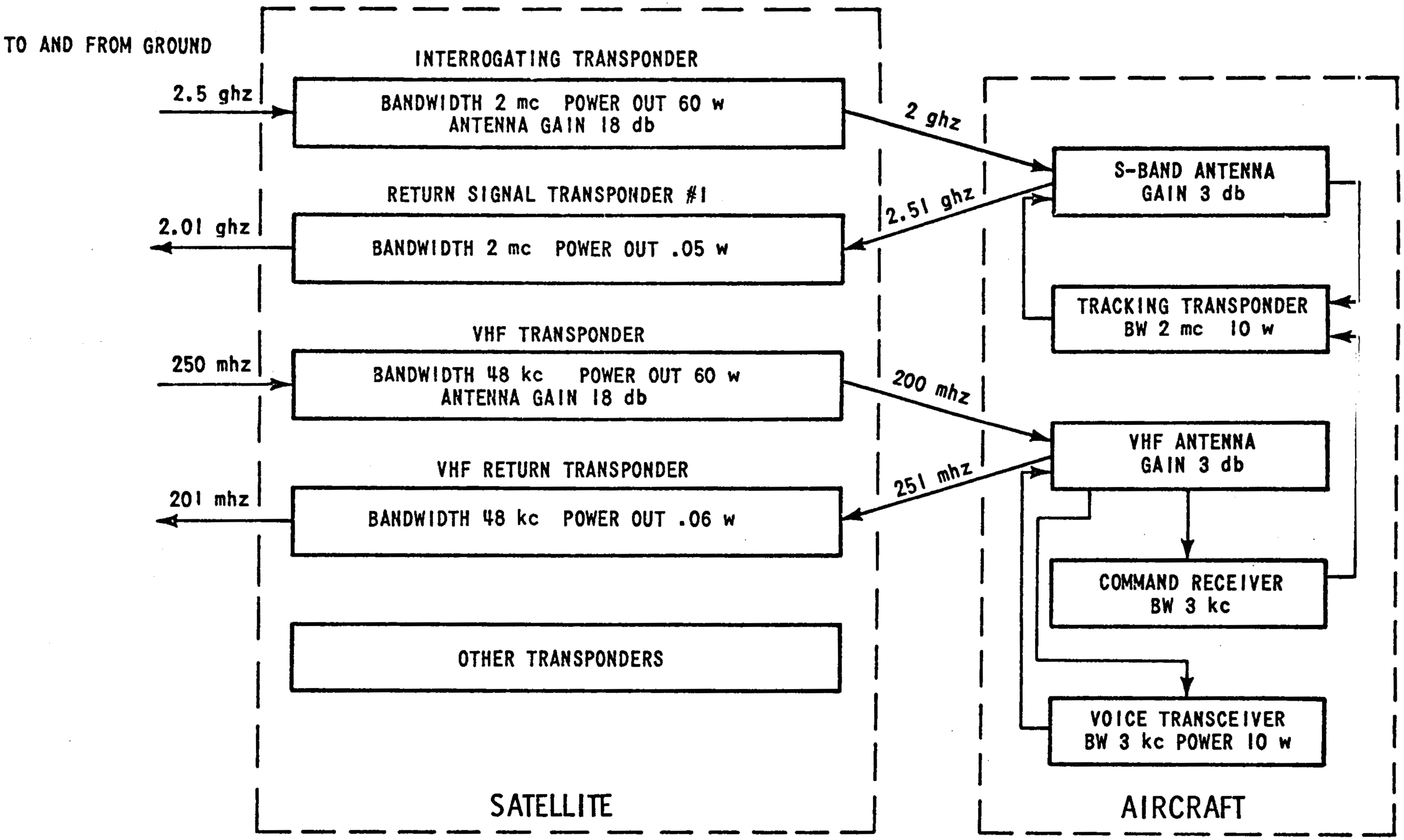

FIGURE 5 - PARTIAL BLOCK DIAGRAM AIRCRAFT CONTROL SYSTEM

BELLCOMM, INC.

Subject: Some Features of a Relay Satellite Air Traffic Control System - Case 101

Date: May 31, 1967

From: C. A. Lovell

Distribution List

NASA Headquarters

Messrs. M. C. Adams/R
P. E. Culbertson/MLA
E. Ehrlich/SAV
S. W. Fordyce/MLA
G. H. Hage/MA
G. J. Howick/UT
L. Jaffe/SA
J. I. Kanter/REG
R. L. Lesher/U
D. R. Lord/MT
H. T. Luskin/MD-T
C. W. Mathews/ML
J. E. Naugle/S
J. D. Stevenson/MO
G. M. Truszynski/T

ARC

Mr. G. A. Smith/FSG

GSFC

Messrs. O. M. Covington/501
F. O. VonBun/507

LRC

Messrs. C. J. Donlan/106
G. B. Graves, Jr./476

Bellcomm

Messrs. G. M. Anderson
A. P. Boysen, Jr.
J. P. Downs
D. R. Hagner
H. A. Helm
J. J. Hibbert
B. T. Howard
D. B. James
C. M. Klingman
J. Z. Menard
G. T. Orrok
I. M. Ross
R. L. Selden
J. M. Tschirgi
R. L. Wagner

Division 103
Central Files
Department 1023
Library